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A Neuroscience Approach to Virtual Reality Experience Using Transcranial Doppler Monitoring

Abstract

Virtual reality enables people to behave and feel as if they were present in a virtual environment and therefore is a useful tool in many fields. In order to study the usefulness of virtual environments, the concept of presence is examined. Up to now, the most common method to measure presence has been to use subjective measures based on validated questionnaires about user experience. However, more objective measurements, such as physiological measurements, are now being considered. In this study, transcranial Doppler (TCD) sonography is presented as a brain activity measurement technique that can be used to study presence in virtual environments. Thirty-two subjects navigated in a virtual environment in different immersive conditions while TCD was monitored. The results show that there are changes in blood flow velocity in the subjects during moments associated with different levels of presence.

1 Introduction

Immersive virtual environments (VEs) allow users to have unique experiences that were never possible before, and although users know from a cognitive point of view that the VE is not a real place, they act and think as if the VE were real. VEs take advantage of people's imaginative ability to psychologically transport their presence to another place.

Since VEs are being used successfully in many fields (Stone, 2002), it is necessary to have a reliable measure of their usefulness. One possible measure (independent of the application) that has been proposed (Held & Durlach, 1992; Sheridan, 1992; Stanney, Mollaghesemi, Reeves, Breaux, & Graeber, 2003) is the concept of presence. Although there is still a lack of concise definitions of the construct of presence, a commonly accepted definition is that presence is the subjective experience of being in one place, even when physically located in another (Baños et al., 2005; Sadowski & Stanney, 2002; Slater & Wilbur, 1997; Sheridan, 1992).

Presence is the process of discerning and validating the existence of self in the natural world, a process humans have engaged in since birth. A sense of presence in a VE derives from feeling as if you exist within, but as a separate entity from, a virtual world that also exists (Heeter, 1992). Other definitions

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avoid the need for a subjective sense of presence by suggesting that the effectiveness of the coupling of perception and action between the user and the (virtual) environment defines presence (Zahorik & Jenison, 1998).

VEs have opened up many new research possibilities and applications in behavioral neuroscience, cognitive science, and psychology (Tarr & Warren, 2002). For example, virtual reality (VR) has been used as a tool to help to understand brain mechanisms related to body ownership (Lenggenhager, Tadi, Metzinger, & Blanke, 2007; Slater, Pérez Marcos, Ehrsson, & Sanchez-Vives, 2008). Moreover, it has been argued recently that VR is not only a tool for neuroscience, but that presence is also an object of study (Sanchez-Vives & Slater, 2005).

But how can presence be measured? A good presence measurement should be: (a) relevant, having a direct connection with presence and its components; (b) reliable, having proven test-retest repeatability; (c) sensitive, having sensitivity to variations in the variables affecting presence; (d) nonintrusive, avoiding unintentional degradation of performance and/or sense of presence; and (e) convenient/portable, low cost, and easy to learn and administer (Hendrix & Barfield, 1996; Jex, 1988; Sadowski & Stanney, 2002). One attempt to measure presence has focused on the use of psychological measurement instruments such as rating scales and subjective reports (Baños et al., 1992; Lessiter, Freeman, Keogh, & Davidoff, 2001; Witmer & Singer, 1998), commonly known as subjective measures of presence. Another group of presence measures has been based on the measurement of the physiological and behavioral responses to stimuli in an immersive VE (Barfield & Weghorst, 1993; Meehan, Insko, Whitton, & Brooks, 2002; Nichols, Haldane, & Wilson, 2000; Wilson, Nichols, & Haldane, 1997; Zahorik & Jenison, 1998).

Up to now, only two brain activity measures have been proposed for presence measurement: electroencephalogram (EEG) and functional magnetic resonance (fMRI). In the earliest published experiments investigating EEG responses to a VE experience, researchers studied human responses to immersion in a VE using EEG (Pugnetti, Mendozzi, Barberi, Rose, & Attree, 1996; Strickland & Chartier, 1997). One of the first studies about EEG and presence discusses properties, advantages, and disadvantages of EEG for presence measurement (Schlögl, Slater, & Pfurtscheller, 2002). Schlögl et al. concluded that EEG is an interesting method to investigate brain activity related to presence research and speculate that adaptive autoregressive parameters can be used to discriminate between states during breaks in presence. EEG has also been used to analyze neural correlates of spatial presence in an arousing virtual environment without interaction, and activations were found in parietal brain areas known to be involved in spatial navigation (Baumgartner, Valko, Esslen, & Jäncke, 2006).

In the only published attempt to relate fMRI and presence, subjects reported experiencing an illusion of presence in VR via a magnet-friendly VR image delivery system despite the constraint of lying down with their head immobilized in an enclosed environment (the fMRI bore) with loud knocking noises (Hoffman, Richards, Coda, Richards, & Sharar, 2003). fMRI results are not reported in the study because the authors fear misinterpretation.

Neural correlates of presence appear to be a promising measure because they potentially provide data that are not influenced by the participant's interpretation as happens with subjective measures. However, the interpretation of brain processes' data can be extremely difficult, since very little is known about the neural processes that are involved in the complex experience of presence.

In the present study, transcranial Doppler sonography (TCD) was used as an alternative brain activity measurement technique that has never been used before in conjunction with VE. TCD is a noninvasive and secure technique based on ultrasounds that was first used in 1982 (Aaslid, Markwalder, & Nornes, 1982). It can be used to determine the characteristics of blood flow in main basal cerebral vessels. Although TCD obtains a measurement of blood flow velocity, there is firm evidence that changes in velocity are closely correlated with cerebral blood flow (CBF) changes (Clark et al., 1996; Kirkham et al., 1986; Newell & Aaslid, 1992). The introduction of bilateral continuous TCD monitoring has resulted in the development of a variety of sophisticated applications to investigate CBF parameters with high temporal resolution. Previous research has shown that

regional CBF increases during mental activities (Risberg, 1986). In fact, brain activity, metabolism, and blood flow are closely related. The neurovascular coupling is the mechanism that adapts CBF to the metabolic demands and the activity of the brain cortex (Iadecola, 1993). When the neurovascular coupling is adequate, the velocity variations that are detected by TCD reflect changes in regional CBF due to brain activation (Daffertshofer, 2001). Empirical evidence indicates that the mean blood flow velocity (BFV) that can be calculated from TCD data is also expected to change when users are doing a cognitive activity in comparison to baseline periods (Vingerhoets, Berckmoes, & Stroobant, 2003; Vingerhoets & Stroobant, 1999; Kelley et al., 1992; Matteis et al., 2001; Knecht et al., 2000).

In this study, we hypothesize that TCD may therefore be a complementary tool to study brain activation and to analyze changes in regional CBF when a subject is being exposed to a virtual environment, and thus it could be a tool to study presence in virtual environments from a neuroscientific point of view.

The main goal was to analyze whether there are BFV variations when subjects are exposed to a VE. The secondary objective was to check whether there is a correlation between accepted measures of presence and BFV when subjects are exposed to different immersive conditions of a VE. Globally, an increment in BFV values is expected during exposure to virtual environments when compared with baseline periods. Since middle cerebral arteries (MCAs) supply mainly lateral parts of the brain involved in the creation of a motor plan, potentially implied in a presence experience, we would expect a BFV increment in these arteries. We also hypothesize increments in anterior cerebral arteries (ACAs), which supply the prefrontal cortex, due to the emotional components and executive control functions potentially related to a presence experience.

2 Methods

2.1 Participants

Thirty-two right-handed volunteers (24 men, 8 women) aged between 17 and 51 years (mean age, 29.93 years; standard error, 1.12) participated in the study. All the participants gave their informed consent prior to their inclusion in the study. Handedness was established by an experienced neurologist during the previous interview without using a formal test.

2.2 Apparatus

A commercially available 2 MHz pulsed-wave TCD unit (Doppler-Box Compumedics, Germany GmbH) was used. This device was chosen mainly due to its portability.

The apparatus was connected to a PC in which QL software was installed. This software was used to receive the data from the Doppler Box and save the selected variables on the PC hard disk for offline analysis. Two dual 2 MHz transducers were connected to the Doppler Box. Probes were attached to the user's head using the probe holder provided with the device. Details about the insonation technique can be found in different studies (e.g., Ringelstein, Kahlscheuer, Niggemeyer, & Otis, 1990). Both hemispheres were simultaneously monitored through the temporal window using two probes capable of simultaneous explorations at two different depths. The first gate of each probe was located between 50 and 55 mm depth in order to register left and right middle cerebral arteries (MCA-L and MCA-R) flow. The second gate was located deeper, between 65 and 70 mm, to take left and right anterior cerebral arteries (ACA-L and ACA-R) flow signals. The captured signal was sampled at a frequency of 100 Hz and a fast Fourier transform (FFT) algorithm was used to obtain the spectrogram. The mean of the envelope of this velocity spectrum (in centimeters per second) was recalculated by the software every 1.3 s.

2.3 Virtual Reality Setting

The study was carried out in a CAVE-like environment (the Reality Center), with four sides: three walls and the floor. The dimensions of the floor were 2.5 × 2.5 m, and the height of the walls was 2.35 m. In order to deliver the images to the different screens, four Barco 909 (Barco, Kortrijk, Belgium) projectors were used.

The machine that was used to generate the images was an SGI Prism (SGI, Sunnyvale, USA). It includes 16 Itanium2 1500 MHz 4 MB L3 CPUs, 16 GB of main memory (NUMA), and eight graphic pipes.

The system used active stereoscopy so liquid crystal shutter glasses, CrystalEyes3 (Real D, StereoGraphics, Beverly Hills, USA) were required for the visualization. The device used to navigate was the Flystick (Advance Realtime Tracking GmbH, Weilheim, Germany), which is a wireless joystick with eight buttons.

An optical tracking system, ARTtrackl (Advance Realtime Tracking GmbH, Weilheim, Germany) was also used. Reflective targets were attached to the CrystalEyes3 and to the Flystick in order to detect their position and orientation.

2.4 Software

The virtual environment displayed in the Reality Center was a maze composed of several rooms and corridors. The environment was programmed using Brainstorm eStudio software (Brainstorm Multimedia, Madrid, Spain), which allows the creation of interactive real-time 3D graphics solutions. In order to navigate, the front button of the Flystick was used to advance in the direction in which this device was pointing, and the rear button was used to move in the opposite direction (backward).

2.5 Procedure

All users had to follow the same protocol during the experiment. When they arrived in the experimental room, they all read a short description of what they were supposed to do during the experiment. The only personal data collected were age and sex.

Users walked into the Reality Center room. Once there, the probe holder with the two ultrasound probes was adjusted to capture BFV values from MCA-L, MCA-R, ACA-L, and ACA-R. The user remained standing up in the middle of the Reality Center for the entire duration of the experiment. There was a training stage. It was confirmed that the user felt comfortable and the cardiac frequency was stable prior to the beginning of the experiment.

Subjects had to navigate in the same virtual environment in two different immersive conditions that caused differences in presence values (measured by questionnaires). The most immersive condition, identified as the free navigation condition, consisted of a free navigation in the virtual environment using the Flystick, for 3:30 min. The Flystick was held with the right hand for the duration of the free navigation condition. Only data from the first 1:20 min were included in the analysis. Before this condition, there was a baseline period used to obtain reference values. Users were instructed to be relaxed during the baseline until the next stage started. Only data from the last 20 s (and at least 15 cardiac cycles) of the baseline periods were included in the analysis in order to guarantee that the signal was stable and that the obtained value was representative of the situation. Similar approaches have been used to calculate the baseline value in other studies (Bäcker et al., 2002; Knecht et al., 2000).

The less immersive condition, called the automatic navigation condition, consisted of watching an automatic navigation through the same virtual environment. Users were completely passive. They only had to watch the automatic navigation that was presented to them. No device was held with their right hand during this period. The display lasted 3:30 min, but only data from the first 1:45 min were included in the analysis. The automatic navigation condition was also preceded by a baseline period.

Head tracking was allowed both in the free and automatic navigation conditions.

Figure 1 shows an image from a real session with one of the subjects who participated in the experiment.

Regarding body movements, the subjects did not make any special movements during the different periods, apart from right arm movements to indicate the direction toward which they wanted to advance inside the virtual environment during the free navigation condition. Involuntary or reflex movements might have occurred, but they were equally possible in the different conditions.

Figure 1. *User watching the video in the Reality Center. The probes are placed on the user's head and connected to the Doppler Box. The Doppler Box is also connected to a PC which runs QL software.*

A neurologist validated the registries for the different vessels during the experiment. Some measurements were discarded because the recorded signals were not reliable (their values were not included in the typical range of BFV in the vessels) or because in the moment of measurement it was impossible to detect a good quality signal corresponding to this vessel. The number of valid measurements is 24 for MCA-L, 22 for MCA-R, 9 for ACA-L, and 6 for ACA-R.

The users' level of presence during the experiment was checked by means of one sufficiently validated method: subjective reports. Once the experiment finished, users had to answer SUS questionnaires (Usoh, Catena, Arman, & Slater, 2000). This questionnaire includes six 7-point Likert-like questions that were adapted to the contents of the virtual environment including references to the maze. The user had to answer the questionnaire twice, once for the free navigation, and again for the automatic navigation condition.

Subjects were ignorant of the goals of the experiment in order to minimize expectation bias.

2.6 Statistical Analysis

Data from SUS questionnaires were analyzed. Apart from the individual responses to the six questions associated with each of the periods (free and automatic navigation), two additional measures were calculated following a similar analysis to previous studies (Usoh et al., 2000): SUS count and SUS mean. SUS count indicates the number of the SUS responses with scores of 6 or 7 among the six questions. SUS mean is the mean score across the six questions. The hypothesis of normality was not supported for most of the variables (in most of them, $p < .05$ in the Kolgomorov-Smirnov test). Taking this into account, a nonparametric test, the Wilcoxon Signed-Rank Test, was selected to compare between SUS responses (dependent variables) in the different experimental conditions (independent variable): first baseline, free navigation condition, second baseline, and automatic navigation condition.

Regarding BFV measurements, the goal was to analyze the modifications in the BFV that may be observed in the free and automatic navigation conditions when compared with the preceding baselines. In order to obtain an indicator of the mean BFV for each period, the mean of BFV values during the time considered for the analysis in that period has been calculated. The Kolgomorov-Smirnov test was applied to the different variables and $p > .05$ was obtained for all of them. Consequently, their normality was assumed and a parametric test was used to compare BFV measurements in each vessel between the different experimental conditions. A repeated measures ANOVA was used for each vessel selecting mean BFV in the period as the dependent variable and experimental period (first baseline, free navigation condition, second baseline, and automatic navigation condition) as the independent variable. No comparisons between vessels were made. If Mauchly's test indicated that the assumption of sphericity had been violated, Greenhouse Geisser corrections were applied. As post hoc tests were needed to obtain paired comparisons, the Bonferroni correction was applied to adjust for multiple comparisons.

In order to analyze whether there are correlations between SUS answers (the individual answer to each

question, SUS mean and SUS count) and BFV values (in MCA-L, MCA-R, ACA-L, and ACA-R) in the different periods (free and automatic navigation conditions), Spearman's rank correlation coefficient was calculated for the different combinations of SUS answers and BFV at each period. Spearman's rho has been used since the hypothesis of normality was not supported for SUS answers.

Moreover, in order to compare between the BFV variation in the automatic and free navigation conditions, an alternative measurement was used: the percentage variation in BFV between the baseline and the activation moments, given in Equation 1 (Matteis et al., 2001, 2006; Troisi et al., 1999; Vingerhoets et al., 2003; Vingerhoets & Stroobant, 1999).

$$BFV(\%) = \frac{BFV_{activation} - BFV_{baseline}}{BFV_{baseline}} \times 100 \quad (1)$$

The normality of the variables that resulted from applying this formula was analyzed using the Kolgomorov-Smirnov procedure. The results showed that the *p* value was greater than .05 for all the variables, so these variables were considered normal and parametric tests were applied to compare the means in the different moments.

The percentage variations in the free navigation and in the automatic navigation conditions for the different vessels were compared using a two-tailed Student's *t*-test for paired samples. The results of all these statistical analysis methods are described in the Results section.

3 Results

3.1 Presence Measurements

The mean values of the responses to the different questions of SUS Questionnaire (questions 1–6), and the values SUS count and SUS mean are shown in Table 1.

In the case of the free navigation condition, the mean value of all answers was 4.83, and the means of the answers to each question were greater than 4.50 in all cases. In the case of the automatic navigation, answers were slightly lower; the mean value of all answers was 3.89, and the means of the answers to each question were always greater than 3.60. The Wilcoxon Signed-Rank Test shows that the response values of the different questions are significantly greater in the case of the free navigation than in the case of the automatic navigation condition. The exact *Z* values and significance values are shown in Table 2.

Table 1. *SUS Responses After the Free Navigation Condition and After the Automatic Navigation Condition**

Measurement	Free navigation	Automatic navigation
SUS count	2.46 ± 0.38	1.19 ± 0.33
SUS mean	4.83 ± 0.23	3.89 ± 0.29
SUS question 1	5.25 ± 0.21	4.19 ± 0.28
SUS question 2	4.84 ± 0.28	4.06 ± 0.27
SUS question 3	4.56 ± 0.34	3.80 ± 0.34
SUS question 4	5.18 ± 0.27	3.80 ± 0.32
SUS question 5	4.56 ± 0.25	4.00 ± 0.28
SUS question 6	4.59 ± 0.24	3.67 ± 0.31

*In the table, the mean value and the standard error of the mean (s.e.m.) are shown. The number of subjects is 32 for the free navigation and 31 for the automatic navigation condition.

3.2 TCD Monitoring

There are differences in the mean BFV values corresponding to the different periods. Their evolution can be seen in Figure 2.

In MCA-L, the results show that mean BFV differed significantly between the four periods: $F(1.682, 38.688) = 44.392$, $p < .001$. Post hoc tests revealed that mean BFV during the navigation (73.091 cm/s) in the free navigation condition was significantly greater ($p < .001$) than during first baseline (66.660 cm/s). Moreover, during the automatic navigation condition (66.587 cm/s) the mean BFV was also significantly greater ($p = .002$) than during the previous baseline period (62.583 cm/s).

In MCA-R, the ANOVA shows that the mean BFV

Table 2. *Results of Applying the Wilcoxon Signed-Rank Test to the Different Variables that Summarize the Responses to the SUS Questionnaires in the Free and Automatic Navigation Conditions*

Measurement	Z	p
SUS count	3.65	<0.001
SUS mean	4.38	<0.001
SUS question 1	3.47	0.001
SUS question 2	3.56	<0.001
SUS question 3	2.69	0.007
SUS question 4	3.65	<0.001
SUS question 5	2.57	0.010
SUS question 6	3.55	<0.001

differed significantly between the four periods: $F(1.947, 40.896) = 33.917$, $p < .001$. Post hoc tests revealed that the mean BFV during navigation (65.712 cm/s) in the free navigation condition was significantly greater ($p < .001$) than during first baseline (59.702 cm/s). Moreover, the mean BFV during the automatic navigation condition (60.514 cm/s) was significantly greater ($p < .001$) than during the preceding baseline period (55.840 cm/s).

The results of the ANOVA test for ACA-L show that the mean BFV differed significantly between the four periods: $F(1.710, 13.679) = 6.843$, $p = .011$. Post hoc tests concluded that the mean BFV in the free navigation condition (48.683 cm/s) was significantly greater ($p = .012$) than during first baseline (41.681 cm/s). On the other hand, during the automatic navigation condition (45.390 cm/s) mean BFV only had a tendency to be greater than during the previous baseline period (42.967 cm/s). However, this tendency did not reach significance.

The results obtained for ACA-R when applying the repeated measures ANOVA test do not support the hypothesis of having different mean velocities in the different periods: $F(1.453, 7.263) = 5.049$, $p = .050$. Post hoc tests do not show significant differences between the different periods. The ACA-R mean BFV is not affected by presence measure differences obtained under different immersive conditions of the VE.

Summarizing the results from the statistical analysis, it can be concluded that there are differences between the mean BFV values for the different periods in some of the vessels. More specifically, the mean BFV during the free navigation condition is significantly greater than the value observed during the baseline for MCA-L, MCA-R, and ACA-L. On the other hand, while the mean BFV during the automatic navigation condition is significantly greater than the value calculated during the second baseline, this is only the case for the MCA-L and MCA-R.

3.3 Correlations Between SUS Answers and BFV in the Different Periods

Interestingly, in analyzing answers to SUS questionnaires for the free navigation and BFV during the free navigation, it was found that SUS mean and MCA-L BFV were significantly correlated ($r_s = 0.451$; $p = .027$). Besides, some answers to individual questions of SUS questionnaires also show a significant correlation with MCA-L BFV (SUS question 1: $r_s = 0.486$; $p = .016$; SUS question 5: $r_s = 0.415$; $p = .044$).

On the other hand, when comparing SUS answers in the automatic navigation and BFV during the automatic navigation, a correlation close to significance was found between SUS mean and MCA-L BFV ($r_s = 0.382$; $p = .065$). Significant correlations were found between the answers to some SUS questions and MCA-L BFV (SUS question 2: $r_s = 0.428$; $p = .037$; SUS question 5: $r_s = 0.611$; $p = .002$; SUS question 6: $r_s = 0.425$; $p = .038$). Besides, a significant correlation was found between SUS count and MCA-R BFV ($r_s = 0.432$; $p = .05$) and also between some answers to SUS questions and MCA-R BFV (SUS question 2: $r_s = 0.501$; $p = .021$; SUS Question 5: $r_s = 0.513$; $p = .018$). The correlation between SUS mean and MCAR-R BFV was close to significance ($r_s = 0.420$; $p = .058$).

No significant correlations were found between the other combinations of variables.

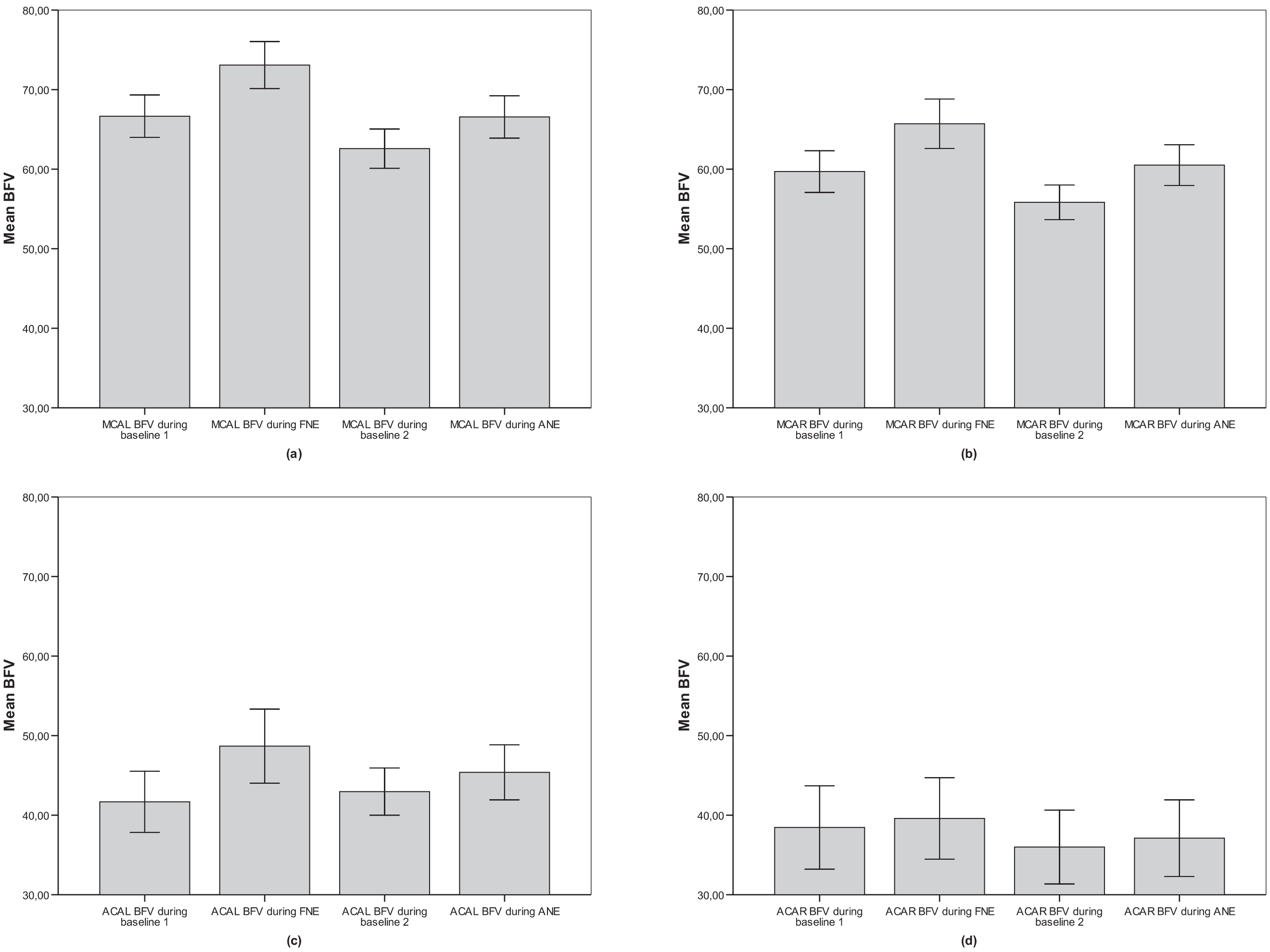

Figure 2. *(a) Mean MCA-L BFV values for the two experimental conditions and their preceding baseline (1: First baseline. 2: Free navigation environment FNE. 3: Second baseline. 4: Automatic navigation environment, ANE). The error bars represent the standard error of the mean (s.e.m.). The number of subjects is 24. (b) Mean MCA-R BFV values for the same periods. The error bars represent the s.e.m. The number of subjects is 22. (c) Mean ACA-L BFV values for the same periods. The error bars represent the s.e.m. The number of subjects is nine. (d) Mean ACA-R BFV values for the same periods. The error bars represent the s.e.m. The number of subjects is six.*

3.4 Observations About Mean BFV Percentage Variations

The percentage variations between mean BFV in the automatic navigation and its preceding baseline, and between mean BFV in the free navigation and its preceding baseline, have been calculated for the different vessels. Their values are graphically represented in Figure 3. The percentage variations obtained are always positive, indicating an increase when changing from baseline to the free navigation or the automatic navigation conditions.

A two-tailed Student's *t*-test was applied to compare the BFV percentage variation in the free navigation with the BFV percentage variation in the automatic navigation in the four vessels. Results for MCA-L and ACA-L show that there is a significant difference between the increase observed in the free navigation and the automatic navigation conditions. The percentage increase is greater in the free navigation (MCA-L: $t(23) = 2.098$, $p = .047$; ACA-L: $t(8) = 5.725$, $p < .001$). However, there is not a significant difference between the percent-

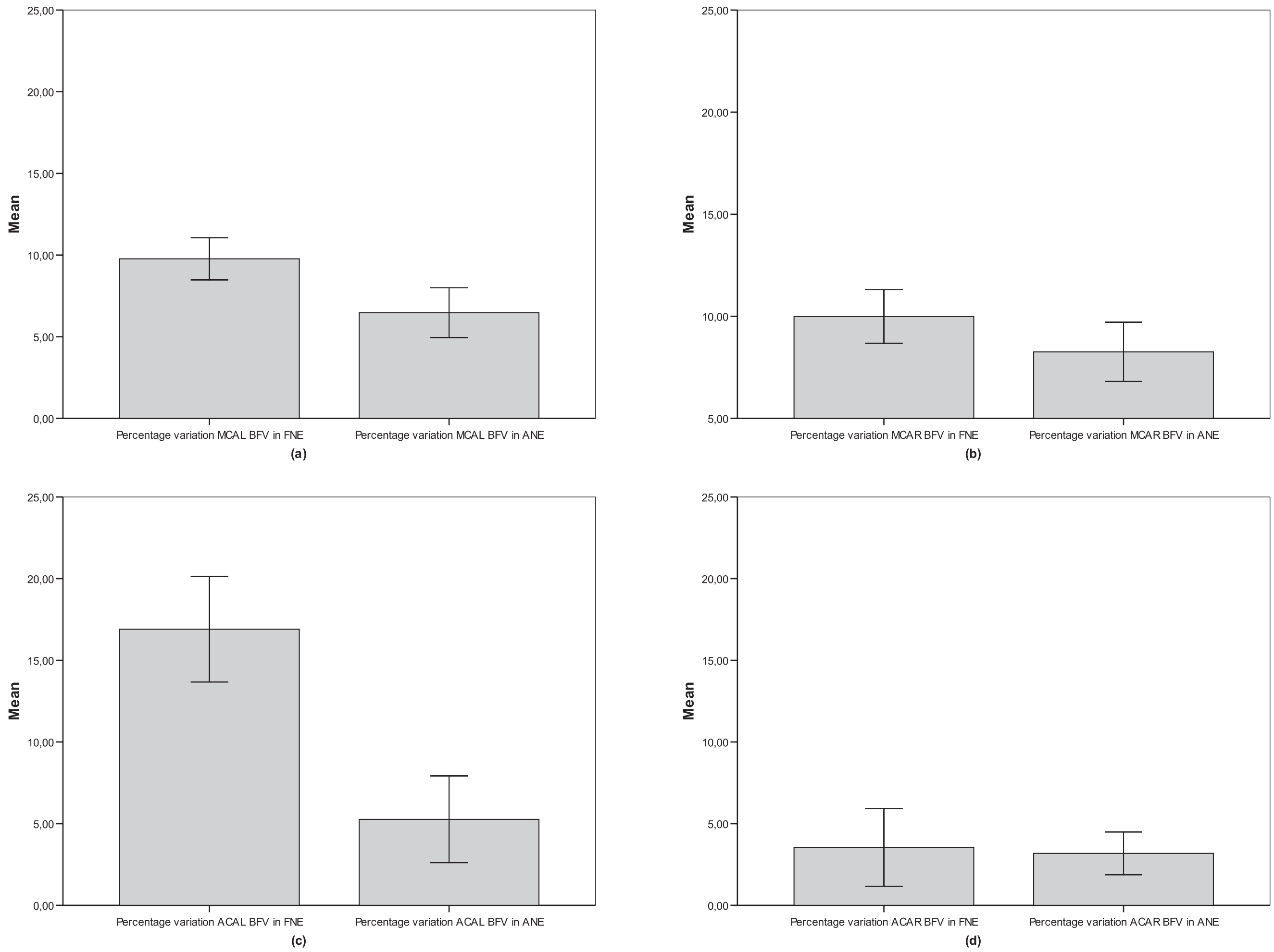

Figure 3. *(a) Percentage variation of mean BFV in MCA-L between the free navigation environment (FNE) and its preceding baseline, and between the automatic navigation environment (ANE) and its preceding baseline. The error bars represent the standard error of the mean (s.e.m.). The number of subjects is 24. (b) Percentage variation of mean BFV in MCA-R between the FNE and its preceding baseline, and between the ANE and its preceding baseline. The error bars represent the s.e.m. The number of subjects is 22. (c) Percentage variation of mean BFV in ACA-L between the FNE and its preceding baseline, and between the ANE and its preceding baseline. The error bars represent the s.e.m. The number of subjects is nine. (d) Percentage variation of mean BFV in ACA-R between the FNE and its preceding baseline, and between the ANE and its preceding baseline. The error bars represent the s.e.m. The number of subjects is six.*

age increase in the free navigation and the increase in the automatic navigation for the right vessels.

Similar patterns have been observed in SUS questionnaires and in BFV increases: BFV percentage variations in MCA-L and ACA-L and SUS questionnaire responses in the free navigation are significantly greater than percentage variations and SUS responses in the automatic navigation.

4 Discussion

The present study shows that there are BFV variations in every monitored vessel when subjects are exposed to a VE. Furthermore, BFV differences depending on presence measures obtained under different immersive conditions of the same VE have been found.

Although fMRI and EEG studies have been proposed

(Baumgartner et al., 2006; Hoffman et al., 2003; Schlögl et al., 2002), in this study an alternative brain activity measurement technique (TCD) that has never been used before in conjunction with virtual environments is proposed. TCD constitutes a complementary neuroimaging tool measuring cerebral perfusion changes due to neural activation and has been widely used to monitor hemodynamic variations in brain activity during the performance of cognitive tasks (Stroobant & Vingerhoets, 2000).

When compared with other methods that are also being considered for the analysis of neural correlates of presence in virtual environments, such as fMRI, TCD has important advantages. It can be used as a measure of brain activity avoiding the exposure of the user to the virtual environment in an uncomfortable way. It is noninvasive, it has a lower cost, and it does not impose mobility restrictions (Lohmann, Ringelstein, & Knecht, 2006). Besides, TCD does not require any special adaptation of the virtual reality hardware in order to be used.

One of the main disadvantages of TCD is its low spatial resolution, which is defined by the size of the cortical areas supplied by the vessel under study. Velocity increases in small vessels cannot generate a noticeable increase in the bigger artery, so activations of small neuron groups in areas of the brain that can be visualized with fMRI cannot be detected using TCD. However, when compared with fMRI, TCD provides a higher temporal resolution that makes it possible to monitor fast changes in BFV values caused by neural activity.

Only right-handed subjects were included in the study in order to obtain a homogeneous group, because qualitative BFV differences in response to cognitive tasks have been observed in right-and left-handed users (Stroobant & Vingerhoets, 2000).

Blood pressure, CO_2, respiratory rate, and other physiological measurements were not controlled during the experiment. First, they were not controlled because including these kinds of measures would have a negative influence on the ecological validity of the experiment. Second, they were not controlled because several studies have proven that these variables do not significantly change while doing the cognitive tasks that are analyzed in the experiments (Cupini et al., 1996; Kelley et al., 1992; Silvestrini, Cupini, Matteis, Troisi, & Caltagirone, 1994). Although most of the experiments using TCD have focused on simple and controlled tests with seated patients, recently it has been published that in healthy subjects with intact cerebral autoregulation, the neurovascular coupling works in an independent way to adapt flow demand to the activity in the different orthostatic situations (Azevedo, Rosengarten, Santos, Freitas, & Kaps, 2007).

Posterior cerebral arteries have not been included in the experiment because it is assumed that an increase in cerebral blood flow velocity in the PCA will occur when the user is exposed to visual stimulation (Panczel, Daffertshofer, Ries, Spiegel, & Hennerici, 1999), as occurs during VE exposure.

In order to compare the different periods, mean BFV values for the different experimental conditions have been calculated, since when neurovascular coupling occurs, velocity variations detected by TCD occur during the first seconds after the onset of the mental task. Studies have found this maximum between 4 s (Knecht et al., 1996) and 20 s (Schnittger, Johannes, Arnavaz, & Münte, 1997) after the onset, with an average peak after 6–9 s (Harders, Laborde, Droste, & Rastogi, 1989; Orlandi and Murri, 1996; Rihs, Gutbrod, Steiger, Sturzenegger, & Mattle, 1995). Velocity remains relatively constant while the activity is maintained.

Moreover, percentage variations between baseline and activation periods have also been calculated to compare the magnitude of the variation that occurs in mean BFV in the free navigation and in the automatic navigation conditions. This procedure eliminates any variability associated with changes in the insonation angle or the vessel diameter (Deppe, Knecht, Henningsen, & Ringelstein, 1997; Schmidt et al., 1999). This is one of the main approaches that has been followed in previous research studies to compare activation periods with the baseline. Each activation period is preceded by a baseline period, and the BFV of each activation period is compared with the BFV of the preceding baseline (Bulla-Hellwig, Vollmer, Götzen, Skreczek, & Hartje, 1996; Cupini et al., 1996; Stroobant & Vingerhoets, 2000).

As already explained, the SUS questionnaire (Usoh et al., 2000) was used for presence measurement. Other

kinds of techniques, such as physiological measurements, have been discarded. Although these measurements can be closely related to presence and are an object of study (Dillon, Keogh, Freeman, & Davidoff, 2000; Slater, Brogni, & Steed, 2003; Wiederhold, Davis, & Wiederhold, 1998), some authors consider that results from these experiments are frequently unreliable (Sadowski & Stanney, 2002) in reflecting the subtle construct of presence. Moreover, using these measurements will result in an additional source of invasiveness for subjects. Consequently, it was decided that it was not worth including these measurements in the present study.

4.1 Presence Questionnaires

Results from questionnaires referenced to the free and automatic navigation periods show that users feel present while navigating inside the environment. The VE used in the experiment induces presence in the users both when they navigate through it freely and when they are just passive spectators (automatic navigation). However, the level of presence that is induced during the automatic navigation is significantly lower than the level of presence that is induced during the free navigation.

4.2 Comparisons Between VE Exposure and Baseline

Results show that BFV values are significantly greater during the free navigation than during the preceding baseline in three vessels: MCA-L, MCA-R, and ACA-L. BFV absolute values are also significantly greater during the automatic navigation than during the preceding baseline, but in this case only in two vessels: MCA-L and MCA-R.

As described in the introduction, there are several factors that can potentially explain the BFV variations observed between the baseline period and the VE exposure. The first factor is the complex interaction between visuospatial interaction tasks, attention tasks, and the creation and execution of a motor plan. When users navigate or passively watch a VE, they have an active role in the experience which is the creation of a motor plan (Holden & Todorov, 2002). This active role cannot be observed during the baseline. Measures in middle cerebral arteries were significantly greater during the VE exposure than during the baseline. These vessels supply mainly the lateral parts of the brain (Angevine & Cotman, 1981). The creation of a motor plan during the VE exposure could be contributing to the increase of BFV that is observed in the middle cerebral arteries, in accordance with results obtained in studies about navigation in videogames (Kelley et al., 1992; Vingerhoets & Stroobant, 1999).

The second possible factor that could have influence on BFV variations is the emotional state changes induced by the VE. In this case, BFV changes will reflect limbic system activation. The medial frontal cortex and most parts of the limbic system are supplied by anterior vessels (Angevine & Cotman, 1981). No significant differences have been found in BFV between the baseline and the VE exposure for ACA-R. This could be due to the reduced number of subjects, which makes it difficult to observe significant differences. In the case of ACA-L, a significant increase of BFV is observed in the free navigation with respect to the preceding baseline. However, there is not a significant increase in the case of the automatic navigation condition. Alternatively, since the user is actively participating in the creation of a complex motor plan, the frontal lobe could be used to make decisions about how to respond to stimuli. There is scarce information in the literature about ACA BFV measurements and their correlates with cerebral functions. In any case, it can be emphasized that the percentage variation observed in ACA-L in our study is much greater than the percentage variation that has been reported in one of the videogame studies that also analyzed ACA-L measurements (Kelley et al., 1992).

Moreover, taking into account that middle cerebral arteries also supply areas of the parietal and frontal lobe involved in the processing of emotion (Tatu, Moulin, Bogousslavsky, & Duvernoy, 1998), any variation in the emotions that the user is feeling can also have an influence in the BFV in middle cerebral arteries (Stoll, Hamann, Mangold, Huf, & Winterhoff-Spurk, 1999;

Troisi et al., 1999). This could potentially explain the observed variations in BFV in MCA-L and MCA-R.

Another factor that cannot be excluded is the possible influence of the order of stimuli presentation to subjects, but previous cognitive studies with TCD did not find any influence of this effect (Harders et al., 1989).

The final consideration could be related to presence. It can be argued that the presence that the user is feeling during the free and automatic navigation conditions could be an additional factor that influences the observed increase. Correlations between answers to SUS questionnaire and BFV values seem to support this hypothesis. In this context, presence could be explained as an activity that affects several brain regions simultaneously and that is difficult to separate from other states. Perhaps presence can be considered a high level cognitive state that is the result of an integration of, among other things, visuospatial interaction tasks, attention tasks, the creation and execution of a motor plan, and emotional states.

4.3 Comparisons Between Free and Automatic Navigation Conditions

Results show that the only significant differences in BFV percentage variations between the free and the automatic navigation conditions occur in the case of left vessels: MCA-L and ACA-L. A significant difference in the percentage variation in the automatic and free navigation conditions is observed in MCA-L, but it could be due to the different navigation states. Given that the user had to navigate and control a joystick in the environment (with right arm movements), the differences could be due to these motor tasks (because subjects are right-handed, they move the right arm to control the joystick and variations in BFV are generated in the left hemisphere; Matteis et al., 2001, 2006; Orlandi & Murri, 1996). The percentage variation in ACA-L is highly significant ($p < .001$). A possible explanation of this variation is that subjects experience a different emotional state in the free and automatic navigation conditions. However, in these conditions the VR setting is the same and the only difference is that users can navigate in the free navigation condition. Further analysis would be required to obtain conclusions. An alternative explanation relies on the level of presence. Since the user feels more present in the free navigation than in the automatic navigation condition, as indicated by the presence questionnaires, a possible relationship between presence level and BFV variations could be considered.

In the case of MCA-R and ACA-R, there are no differences in BFV that can be related to different presence ratings in both situations (free and automatic navigation conditions).

4.4 Final Comments

This study has proven that TCD is a valid technique for measuring blood flow changes secondary to brain activity under different immersive states in virtual environments. The results show that immersion in a virtual environment generates generalized changes in brain activity that can be detected using TCD techniques. These changes could be related to the sense of presence, although further research must be conducted in order to deepen this analysis.

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